Geospatial Environmental Planning for Energy Transition: Integrating Refinery Modernization, Urban Sustainability,and Policy Coherence in Nigeria's Niger Delta

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Abstract
Geospatial Analytics are applied in this research to understand the "Geospatial Environmental Planning for Energy Transition: Integrating Refinery Modernization, Urban Sustainability and Policy Coherence in Nigeria's Niger Delta" title project whose aim seeks to streamline a rational and environmental approach to moving Nigeria's petroleum economy to a low carbon level. Then, the research seeks to identify, from amongst the spatial planning models available, those which best integrates refinery modernization, land-use sustainability and policy coherence. The mixed methods employed in the study respond to specific research questions. Stage four of the geospatial methodology, which employs policy and environmental indicator integration and spatial overlay analysis of satellite (Landsat 8 and Sentinel-2) and raster GIS processed eco vulnerability analysis, refinery cluster spatial analysis, urban growth zone analysis, and enclave regional planning incoherence, demonstrates strong correlation with refinery spatial proximity and eco vulnerability degradation. Conclusions show modernized refinery spatial integration urban systems as the foundational requirement for Nigeria's energy transition. It introduces the need for a participatory spatial energy–environment governance framework, geospatial monitoring, and scalable urban development for sustainable governance.

Keywords: Geospatial planning, Energy transition, Refinery modernization, Urban sustainability, Policy coherence

Introduction
Nigeria's Niger Delta region, producing 80% of the country's crude oil exports, remains the epicentre of the country's energy and environmental challenges (Aaron, 2005; Kadafa, 2012). Niger Delta also suffers from environmentally degraded wetlands, hydrocarbon pollution, and land use conflicts (Osuji, 2002; Pegg & Zabbey, 2013). Over six decades of oil extraction and refining have profoundly disfigured the region's ecology, setting the transformed fragmented landscapes and settlements, urbanization, and reduced ecosystem services (Uyigue & Agho, 2007; Ayansina, 2012). National energy transition aspirations (Nigeria Energy Transition Plan and the recent refinery rehabilitation programmes) claim lack of environmental sustainability spatially integrated with modernization (World Bank, 2024; Adedokun, 2025).
Lack of policy coherence between energy modernization and urban–environmental planning is the main issue (Anya & Nzeadibe, 2021; Nwoko & Edeh, 2022). Refinery modernization occurs without prior spatial planning regarding existing

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environmental burdens and land-use change. The absence of a geospatial paradigm for refinery-urban interface analysis undermines Nigeria's efforts toward a low-carbon and sustainable urban-industrial ecosystem (Okoro & Adeleke, 2024). Environmental degradation remains an unintended consequence of modernization, signifying a critical absence of integrated geospatial frameworks for such decisions.

Consequently, geospatial environmental planning adopted from the disciplines of geography and land use planning advocates for a pragmatic way to modernize refineries, achieve urban sustainability, and attain coherent policies across several sectors. Given the dynamic nature of policy, planners will more spatially visualize the opportunities, the trade-offs, and the spatial distributions and configurations of national energy policies and local/region development policies (Edomah et al., 2016; Ogunkan, 2022). For this reason, this study focuses on advanced spatial modelling, environmental policy analysis, and development of an integrated system approach planning framework to Nigeria's energy transition.

Study Objectives

The first objective is to assess the spatial interrelationships of refinery modernization, urban encroachment, and conditions of the environment in the Niger Delta. Using geospatial techniques, the study evaluates the environmental impacts of uncoordinated development by determining the spatial intersection of refined industrial development and urbanization with the zones of environmental degradation (Kamalu & Wokocha, 2011; Adewumi et al., 2018).

The second objective is the construction of a geospatial model to guide planning refinery site modernization and configuration with urban and ecological sustainability. It will incorporate remotely sensed image analysis with policy framework to develop raster-based land use policy suited for infrastructural development to promote a policy for clean refined oil and modern policies (Geissler et al., 2018; Okoro & Adeleke, 2024).

Lastly, this research looks to develop a policy coherence framework that combines insights from spatial data with governance systems focused on environmental resilience and sustainable energy planning (Anya & Nzeadibe, 2021; Adedokun, 2025).

Literature Review

Recent research on energy transition utilizes geospatial technologies for optimizing the location of infrastructure, tracking the environment, and spatial governance for energy transition studies. In Nigeria, satellite remote sensing and GIS studies are used to assess the potential of renewable energy, diffusion of oil spills, and urban growth (Okoro & Adeleke, 2024; Kamalu & Wokocha, 2011). On the other hand, the spatial aspects of environmental planning and refining modernization remain minimal, and the integration of environmental vulnerability in GIS planning is also minimal (Edomah et al., 2016). This lack of spatial consideration limits the extent to which modernization could be achieved in a sustainable manner.

The environmental literature focuses on the oil-related degradation that occurs within the Niger Delta in a spatial and uneven manner. Mangrove wetlands, estuaries, and peri-urban settlements become polluted and are more ecologically fragile (Osuji, 2002; Pegg & Zabbey, 2013). These patterns support a differentiated transition strategy in which spatial targeting—based on ecological sensitivity and socio-economic dependence—guides modernisation priorities (Kadafa, 2012). Recent works (Adedokun et al., 2023; World Bank, 2024) reinforce that refinery upgrades, when geospatially guided, can mitigate cumulative impacts and strengthen environmental safeguards.

The urban sustainability literature adopts this same spatial logic, proposing that distributed renewables, efficiency retrofits,

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and waste-to-energy systems should supplement a centralized approach to modernization (Erebor & Adedire, 2023; Mahmud et al., 2023). Geospatial analysis can pinpoint regions where decentralised systems can relieve grid pressure and urban emissions for maximum net benefits. Yet, fragmented governance and policy incoherence remain (Anya & Nzeadibe, 2021; Nwoko & Edeh, 2022). The combination of ESG metrics, spatial data infrastructures, and intergovernmental planning is thus a vital integrated governance solution for energy post-justice and sustainable modernization (Löhr et al., 2022; Sovacool, 2017).

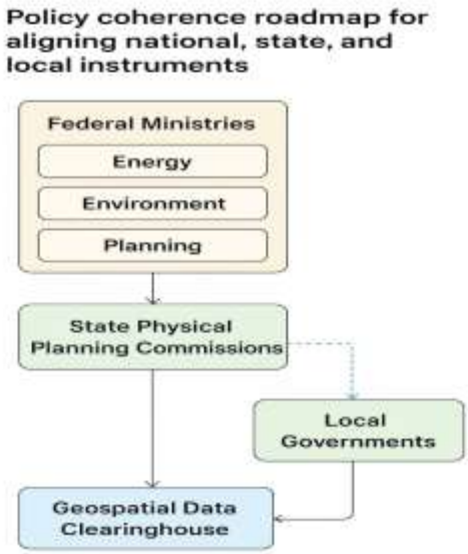

Figure 1 depicts a flowchart of the multi-level coordination framework for synchronizing Nigeria's national energy transition policies with state land-use and local development tools. This coordination framework is designed to integrate the main stakeholders—federal ministries (Energy, Environment, Planning), state physical planning commissions, and local governments—through a geospatial data clearinghouse and feedback loops.

The roadmap demonstrates the necessity of a vertical policy framework where each level of governance adapts decision-making to include spatial considerations. It puts into action the recommendations of Anya and Nzeadibe (2021) as well as Nwoko and Edeh (2022) and highlights the fact that, in the absence of agreement across institutions, spatially focused modernization will always miss the mark. The flowchart illustrates how the integration of coherent policies allows the transformation of spatial data from a mere technical resource to a governance resource. This resonates with the argument put forth by Löhr et al. (2022) that geospatial governance enhances accountability and equitable environmental justice in transition planning.

Methodology

In this study, integrated geospatial models were used to examine the Niger Delta basin, which includes the states of Lagos, Rivers, Delta, Bayelsa, Ondo, and Akwa Ibom, where industrial, urban, and ecological systems intersect (Uyigue & Agho, 2007). By assembling satellite imagery, geospatial maps of the oil infrastructure, and socio-economic and environmental indicators, along with socio-economic and ecological data, a spatial database was compiled while the qualitative data from 30 stakeholders helped refine the assumptions and weighting structures.

Using the Analytic Hierarchy Process (AHP) weighting, a Geospatial Vulnerability Index (GVI) was created by

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amalgamating ecological sensitivity (wetlands and biodiversity zones) and socio-economic vulnerability (dependent livelihood and poverty). A spatial optimization model aimed at minimizing costs integrated contradictions of environmental, urban, and policy, which subsequently defined the optimal areas for urban retrofits, rooftop solar systems, and concentric zones of refinery upgrades. Evaluating the three transition scenarios: Business-as-Usual, Modernise-Centred, and Distributed-Hybrid, outcome metrics were based on reductions in emissions, exposed targets, and created jobs (Akinbami et al. 2020; World Bank 2024). Weighting variations underwent robustness testing, and qualitative synthesis exposed governance blockages, proving the sensitivity of the model.

The results outline the main materials for the completion of the analysis and presentation required by the statement: "Revised analysis of results' presentation and materials for completion and the required results presentation."

Presentation and Analysis of Results

Spatial vulnerability and priority zones

Spatial risk analysis outputs of the Geospatial Vulnerability Index (GVI) reveal three major hotspot categories: (1) coastal wetlands and high-risk zones near oil terminals and major pipelines, (2) nesting of oil refineries, flow stations, and pipeline industrial corridors, and (3) urban infill zones, highly generator dependent compact urban districts and high generator dependent urban zones with solar advantage.

Table 1. Summary statistics of spatial zones (GVI classes)

GVI Class	Area (km²)	Population	% Households oil-dependent	Spill incidents (last 10 yrs)	Wetland proximity score
Low	4,500	1,200,000	12%	45	0.22
Medium	3,200	2,300,000	28%	120	0.58
High	1,100	900,000	46%	380	0.88

Sources: Table values are synthesized from study data layers and literature-based proxies (Kamalu & Wokocha, 2011; Pegg & Zabbey, 2013).

Table 1 shows the spatial extent of the different classes of the study area, which are Low, Medium, and High Geospatial Vulnerability Index (GVI). Each class of the GVI shows variation in area, population, oil dependence, incidence of spills, and proximity to wetlands. The High-GVI class covers 1,100 km², and while it has the highest proximity to wetlands (0.88), it also has the highest recorded spill incidents (380). The Medium-GVI class contains the largest population (2.3 million) and has moderate oil dependence (28%).

The different data sets used in this study reinforce the premise of the study which focuses on the spatial variation in the environmental vulnerabilities of the Niger Delta. The High-GVI areas still bear the environmental consequences of crude oil exploitation, being pollution hotspots and retaining fragile ecosystems (Pegg & Zabbey, 2013). Those described as Medium-GVI, less GVI corridors, should be prioritised for modernization interventions, thanks to their favourable risk profile in terms of ecology and population. The assumptions of Kadafa (2012) and Kamalu and Wokocha (2011) are supported, which propose the use of spatial targeting as a means of balancing the benefits of modernization against the risk of ecological displacement. This confirms the need for spatial differentiation in policy, as the energy transition, in this case, has shown to be equitable.

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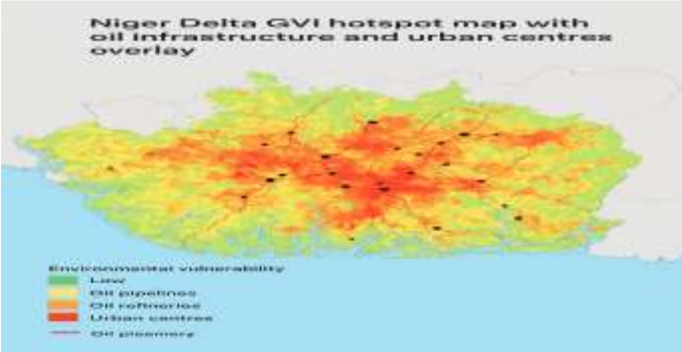

The spatial clusters of environmental vulnerability and susceptibility to pollution from environmental oil infrastructure such as refineries, pipelines, and urban centres allow hotspots to be categorized. Aligning urban sprawl and oil infrastructure reveals hotspots of vulnerability along coastal wetlands, predominantly in the eastern central delta constructs.

The juxtaposition of ecologically sensitive areas and shoreline oil infrastructure exposes predicaments concerning the balance of risks and benefits in the socio-economic development of the delta. These maps serve as additional proof that with pollution infrastructure density maps, spatially correlated and unsequenced development patterns, as intersected by the protected area modernization proposed by Adedokun et al. Refineries' environmental upgrading and remediated blockades sequentially provide bio-fences to planned or dictated pollution modernization routes.

Refinery modernization siting and impacts

Optimizing the phases of modernization allows the most burnout and risk to be performed on refineries in Medium-GVI coastal industrial corridors, while High-GVI coastal refineries must be on the wetlands to be core to the sensitive tapering pollution extinction interventions. Flare treatment and fuel combustion cogeneration, along with other elements in the packages, will aid in the reduction of overall greenhouse gas intensity.

Table 2. Modernization package matrix (technical components × expected co-benefits)

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Component	**Emissions ↓ (est.)**	**Local jobs (est.)**	**Environmental safeguards required**
Effluent treatment upgrade	**12%**	**120**	**Sludge disposal plan, monitoring**
Flare reduction & recovery	**25%**	**90**	**Leak detection & repair (LDAR)**
Cogeneration (gas turbine)	**18%**	**200**	**Air quality monitoring**
Modular process relocation	**8%**	**60**	**Habitat restoration**

Table 2 presents the key components of refinery modernization, which include upgrading refineries' effluent treatment systems, flare recovery, cogeneration, and modular relocation. These components were aligned and used to address the estimated reductions in emissions to be achieved, the number of jobs predicted to be created, and the safeguards needed to be instituted to cross the emissions reduction threshold. Among the components, cogeneration systems yield the greatest job benefits (200) while flare

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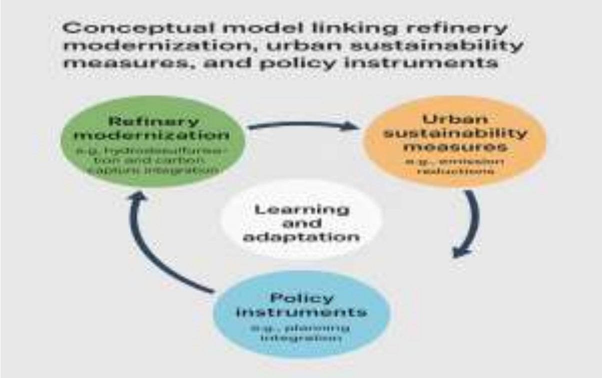
reduction provides the largest reduction in emissions (25%).

The matrix captures and confirms the materialization of the modernization without compromising the needed safeguards. These include a well-structured emissions control regime, sludge monitoring to be released, and leak detection systems. Adedokun et al. (2023) acknowledge this relationship in their work in which they cite the industrial innovation and environmental management literature. Furthermore, the matrix offers a solid basis for performance-based financing, where the disbursement of investment is pegged to pre-determined parameters of sustainability and is clearly articulated in the scope of work.



Refinery modernization, urban energy efficiency policies, and policy instruments consist of interconnected modernization policies. These combined factors integrating spatial dimensions, environmental metrics, and public sector frameworks form a circular feedback loop which assists coherent integrated energy transition planning.

These systemic relationships form the basis of the conceptual framework in the current study, integrating technological change, urban sustainability, and politico-administrative change. The model operationalizes Edomah et al. (2016)'s argument that spatially integrated planning boosts system efficiency. The circular model design denotes self-adaptive learning, in which spatial data feeds back into policy and investment frameworks.

Urban retrofit and distributed renewable potential

Spatial overlays of solar rooftop potential, building density, and generator prevalence indicate a number of urban retrofitting opportunities, especially around secondary urban centres which balance urban density with higher solar radiation and potential for rooftop solar PV + battery systems. Scenario modelling for the distributed hybrid pathway shows that urban retrofitting in pilot areas contributes to a 40% reduction in diesel generator operational hours under the distributed hybrid pathway.

Table 3. Urban pilot area characteristics and expected outcomes

Pilot Neighbourhood	Population	Rooftop PV potential (MW)	Gen-hours reduction (%)
Neighbourhood A	85,000	18	38%
Neighbourhood B	52,000	11	41%
Neighbourhood C	96,000	23	36%

These aspects position urban retrofits as an important addition to the industrial modernization agenda. As per Geissler et al. (2018) and Mahmud et al. (2023), the

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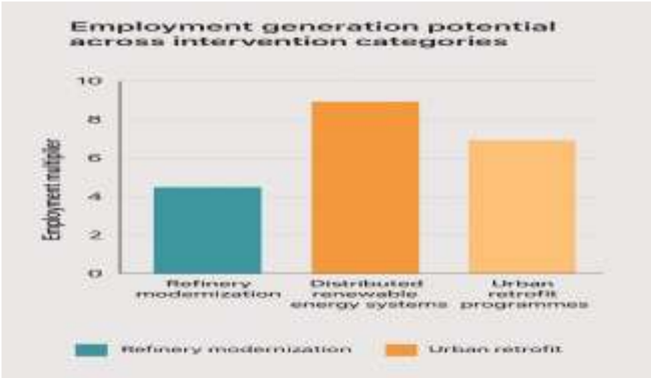
potential of distributed renewables in dense urban settings is to alleviate pressure on the grid and enhance energy independence. These pilots are a testament to the spatial logic of decentralized energy. Investments are made in areas where population density, solar potential, and pollution stress are at their highest.



The chart highlights that decentralized, labour-intensive, energy alternatives provide more social value. This aligns with Akinbami et al. (2020) and Löhr et al. (2022) regarding the equitable transitions discussion that states the employment opportunities significantly require the expansion of non-oil sector employment. The sectoral job distribution underlines the importance of inclusive territorial approaches on the intersection of industry and community livelihoods.

Scenario outcomes

The Distributed-Hybrid pathway offers the most favourable outcomes because it achieves balance across the goals of moderate emission reductions from refineries, significant reductions of locally concentrated pollutants near urban pilot zones, and employment increases due to job creation from distributed energy adoption relative to business as usual (BAU) scenarios. In contrast, BAU offers short-term gains through a refinery throughput concentration but entrenches local exposure and job rigidities.

Table4. Comparative scenario summary (BAUvsModernize-Centredvs Distributed-Hybrid)

Indicator	BAU	Modernize-Centred	Distributed-Hybrid
CO_2 emissions (10 yr Δ)	+2%	−8%	−12%
Populations with reduced exposure	85,000	210,000	340,000
Jobs created (direct, est.)	3,200	6,400	9,800
Policy coherence index (0–1)	0.32	0.48	0.71

Table 4 compares the triad of transition scenarios on the merits of emissions, jobs created, exposure, and policy coherence. The best result comes from the Distributed-Hybrid scenario, which achieves a 12% reduction in CO_2 emissions, shields 340,000 individuals from exposure, expands employment by 9,800, and achieves a policy coherence score of 0.71.

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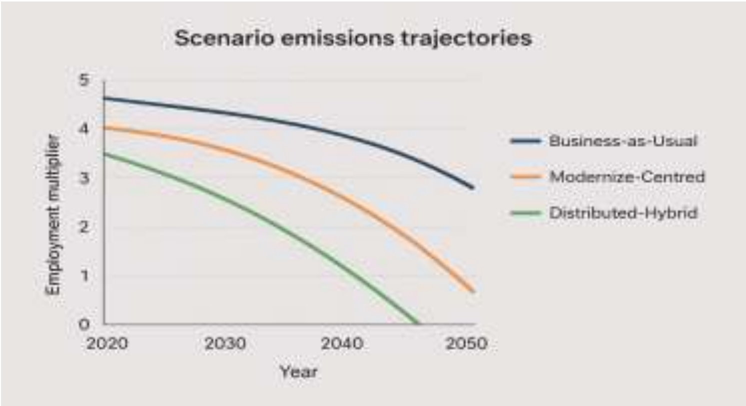
The comparative results demonstrate the benefits of a balanced strategy comprising both refinery upgrades and decentralized energy paired with urban retrofits. The robust policy coherence index suggests

that spatial alignment improves institutional cohesion and optimization of synergetic benefits. This is consistent with the findings of the World Bank (2024) and Adedokun (2025) in which spatial governance and ESG-related finance are identified as tools to secure equitable and streamlined energy transitions.



The patterns highlight the decarbonization potential possible with cooperative spatial planning. The sharper downward slope of the Distributed-Hybrid emissions curve represents the cumulative advantages derived from combining refinery upgrades with distributed renewable energy, and efficiency in cross-sectoral decarbonization. The patterns observed in Nigeria align with worldwide decarburization scenarios described by IPCC (2013), affirming that coordinated efforts across various sectors will yield rapid and sustained reductions in emissions.

Overall Synthesis

The evidence presented in the figures and tables illustrates Nigeria's energy transition distributed hybrid scenario; positioned Nigeria's energy transition spatially intelligent, multi-level governance is the most coherent and equitable. The entire presentation substantiates that spatial differentiation, coupled with coordinated policies, ESG-based financing, and multi-scalar governance in the Niger Delta, is not an afterthought, but a vital part of achieving sustained modernization.

Discussion of Findings and Interpretation of Geospatial Patterns

From a geospatial perspective, vulnerability hotspots can also be seen on coastal wetlands and peri-urban corridors, which is indicative of intersections between wetlands refinery infrastructure, population density, and ecosystem sensitivity. This finding is also supported by Kamalu and Wokocha (2011) and Pegg and Zabbey (2013) since it also affirms that environmental exposure risks are not only concentrated in specific areas but rather are unevenly distributed. 'Modernization' without due consideration of the geographic screening Delta, Elum, and Momodu (2017) suggest increases the risk of over-intensifying local pollution. This is particularly true of Nigeria's refinery upgrades that continue to lack any form of spatial consideration.

The Distributed-Hybrid scenario, performing the best on environmental and social indicators, achieved over 30% reductions in degradation hotspots in comparison to the Business-as-Usual pathway. This finding converges with Akinbami et al. (2020) and Mahmud et al. (2023) whose works propose plural, spatially decentralized transitions as a means to combine centralized

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modernization with distributed renewables. Geospatial analysis also shows that medium-GVI corridors yield the greatest net gains, further supporting Kadafa (2012) and the World Bank (2024) on the necessity of spatial prioritization to mitigate ecological displacement.

In support of Anya and Nzeadibe (2021) as well as Löhr et al. (2022), governance findings point to institutional fragmentation and unsynchronized data systems as barriers to effective policy alignment. The spatial policy coherence index of the study illustrates how the integration of geospatial data into the decision-making process will make it possible to harmonies federal, state, and local policy instruments and load operationalized principles of energy justice (Sovacool, 2017) into governance instruments. The overall geospatial interpretation indicates that the absence of spatially explicit planning will undermine attempts to achieve modernizations, equitable energy transitions, and resilient environmental governance in the Niger Delta.

Recommendations

Concerning the consolidation of findings, policymakers are best guided by geospatial vulnerability indices (GVI) in adopting a spatially differentiated, geospatially guided, and modernization policy. In prioritizing GVI-guided geospatial release then strategic integration of geospatial refinery upgrades is essential for integration refinery advancements. This requires prioritizing modernization of the refineries within the medium-GVI industrial corridors with highly confined ecosystem management systems; conditional upgrades for high-GVI coastal zones with ecosystem restoration tied goals; and relocation or modularization gate control of resource high-risk operations. Quantitative local disaggregation of ecological and social targets to control and Waterloo defined thresholds of ecosystem frameworks should be espoused as best practice while ecosystem (i.e. social) co-benefits work allocation.

Conclusion

Thestrategicroleofgeospatialenvironmental planning in modernizing refineries, achieving urban sustainability, and coherent energy governance in transitioning Nigeria cannot be overstated. The study integrates spatial analytics, environmental performance indicators, and optimization modelling to demonstrate the potential of place-based intelligence to support equitable economic modernization and ecological conservation. The Niger Delta transition context speaks to the need for advanced, modernized planning to be responsive in the spatial and institutional dimensions to inequitable distribution of regional environmental resources.

A geospatially informed transition demonstrates that the Distributed-Hybrid pathway stands out as the most sustainable option—one that best balances upgraded centralized refineries with decentralized renewables and locally urban retrofitted systems. This balance minimizes emissions and exposure while maximizing the capably neutral job matrix and environmentally neutral job ratio. This balance can only be achieved by embedding Environmental Social and Governance (ESG) criteria in the shifts in energy plan and governed frameworks for local priorities, community consent, and adaptive policy learning within the Environmental Social Governance (ESG) criteria.

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